Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 1 February 2008 (MN LATEX style file v1.4)

On the pulsation parallax of the variable star RR Lyr

G.Bono[1], F.Caputo[1], V.Castellani[1,2], M. Marconi[3], J. Storm[4]

[1] *INAF-Osservatorio Astronomico di Roma, via di Frascati 33, 00040 Monte Porzio Catone, Italy bono/caputo/vittorio@mporzio.astro.it*

[2] *INFN - Sezione di Ferrara,*

[3] *INAF-Osservatorio Astronomico di Capodimonte, via Moiariello 16, 80131 Napoli, Italy marcella@na.astro.it*

[4] *Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany jstorm@aip.de*

ABSTRACT

We show that a straightforward application of the predicted relation connecting the absolute K magnitude of fundamental RR Lyrae variables to their period and metal content, together with current evolutionary predictions on the mass and luminosity of Horizontal Branch stars, supply a distance estimate to the prototype star RR Lyr in close agreement with the recent parallax determination by HST (Benedict et al. 2002), largely unaffected by the interstellar extinction correction. Adopting $< A_V >$=0.12±0.10 mag as a safe estimate of the extinction correction to RR Lyr, we obtain a "pulsation" parallax π_{puls}=3.858±0.131 mas which agrees quite well, and with a smaller formal error, with the HST measurement (π_{abs}=3.82±0.20 mas) and with the weighted average of HST, Hipparcos, and ground-based determinations ($< \pi_{abs} >$=3.87±0.19 mas). This result suggests that near-infrared magnitudes and pulsation models could constrain the distance to well-studied RR Lyrae stars, both in the field and in globular clusters, with an accuracy better than current direct trigonometric measurements.

Key words: globular clusters: distances – stars: evolution – stars: horizontal branch – stars: oscillations – stars: variables: RR Lyrae

1 INTRODUCTION

The intrinsic luminosity of RR Lyrae variables and its dependence on metal content are widely debated issues in the recent literature, mainly because of the relevance in determining the distance to globular clusters, and in turn the age of these old primeval stellar systems. Unfortunately, neither empirical nor theoretical approaches have provided firm estimates of the absolute magnitude of RR Lyrae stars yet (see Caputo et al. 2000, and references therein), nor the trigonometric parallaxes measured by HIPPARCOS for a limited sample of field RR Lyrae stars are precise enough to put sound constraints on such a parameter (see Cassisi et al. 1998; Fernley et al. 1998, hereinafter F98; Groenewegen & Salaris 1999). In this context, new and accurate data on the distance to these variables appear of great relevance and could help to establish the absolute distance scale of RR Lyrae stars.

In a recent investigation, Benedict et al. (2002, hereinafter B02) use new astrometric data collected with FGS 3, the interferometer on board the Hubble Space Telescope (HST), to provide an accurate estimate of the absolute trigonometric parallax of the variable star RR Lyr, namely π_{abs}=3.82±0.20 mas. The uncertainty affecting this estimate is approximately a factor of three smaller than the uncertainty of the HIPPARCOS parallax (π_{abs}=4.38±0.59 mas; Perryman et al. 1997), and dramatically smaller than the error affecting the average ground-based measurement (π_{abs}=3.0±1.9 mas; van Altena, Lee, & Hoffleit 1995, hereinafter YPC5). According to the HST parallax, one derives for RR Lyr a true distance modulus μ_0=7.090±0.114 mag, while the weighted average of HST, Hipparcos, and YPC5 results ($< \pi_{abs} >$=3.87±0.19 mas) yields μ_0=7.061±0.107 mag.

In this letter we show that a straightforward application of theoretical constraints concerning the predicted K-band magnitude of fundamental RR Lyrae stars does provide a distance to RR Lyr which is in close agreement with the HST result, and with a smaller formal error.

2 *K*-BAND PARALLAX

It has already been suggested that several problems affecting the RR Lyrae distance scale can be overcome using K-band magnitudes. In a seminal empirical investigation, Longmore et al. (1990) found that RR Lyrae stars do obey a tight Period-Luminosity relation (PL_K) in this band. Moreover, K-band data present additional advantages when compared with optical ones: they are marginally affected by uncertain-

ties on reddening and present a smaller dependence on metal content, as well as a smaller luminosity amplitude. These interesting features were soundly enriched by the empirical evidence brought forward by Longmore et al. (1990) that the slope of the PL_K relation is, within observational errors, quite constant when moving from metal-poor to metal-rich cluster RR Lyrae stars.

These findings have recently found theoretical support. Based on a wide grid of nonlinear, convective pulsation models, and using bolometric corrections and color-temperature transformations by Castelli, Gratton & Kurucz (1997a,b), we predicted (Bono et al. 2001, Paper I) that RR Lyrae stars obey a very tight relation connecting the absolute K-band magnitude, period, intrinsic luminosity, and metal abundance, i.e. a PLZ_K relation. This relation is characterized by a mild dependence on stellar luminosity and metal content.

We have implemented this theoretical framework by computing new sequences of fundamental (F) and first-overtone (FO) models that cover in great detail the range of metallicity (Z=0.0001 to Z=0.02), luminosity ($\log L/L_{\odot} \sim$ 1.5 to 1.8), and mass ($M/M_{\odot} \sim$ 0.5 to 0.8), as expected for field and globular cluster RR Lyrae stars, adopting a helium-to-metal enrichment ratio $\Delta Y/\Delta Z \sim 2.5$. The full set of F and FO models will be presented and discussed in a forthcoming paper (Bono et al. 2002, Paper III). Here we report that, according to this theoretical scenario, the predicted absolute K magnitude of F pulsators is correlated with the period (P in days), metal content (Z), stellar mass (M in solar units) and luminosity (L in solar unitis) as follows:

$$M_K = 0.511-2.102 \log P+0.095 \log Z-0.734 \log L-1.735 \log M/M_r \quad (1)$$

with an intrinsic standard deviation of σ_K=0.016 mag. The values of the reference mass M_r for the various assumptions on the metallicity are given in Table 1, as chosen to roughly account for the correlation between metal content and mass of Zero Age Horizontal Branch (ZAHB) models populating the RR Lyrae instability strip, i.e. for effective temperatures ranging from 5900 to 7100 K. For the sake of comparison, Table 1 also lists the evolutionary mass (with an average uncertainty $\sim$ 2%) of ZAHB models with $\log T_e$=3.85 and 3.80, as predicted by evolutionary computations available in the recent literature.

In agreement with the conclusions presented in Paper I, we find that the predicted fundamental PLZ_K relation presents a quite small dependence on stellar luminosity (a variation of 0.1 dex in luminosity yields $\delta M_K \sim 0.07$ mag), and metal abundance (a variation of 0.3 dex in metallicity yields $\delta M_K \sim 0.03$ mag). This evidence suggests that the near-infrared magnitudes of RR Lyrae stars could be excellent standard candles to estimate the distance to field and globular cluster variables.

We can now use the predicted PLZ_K relation together with the observed near-infrared magnitude $K = 6.54 \pm 0.04$ mag (Fernley, Skillen & Burki 1993) of RR Lyr to derive a *pulsation* parallax to be compared with the HST trigonometric measurement.

According to B02, the interstellar extinction toward RR Lyr is $< A_V >$=0.07±0.03 mag. Since $A_K \sim 0.11\ A_V$ (Cardelli et al. 1989), this yields that the infrared extinction correction is at most of the order of 0.01 mag and therefore it can be neglected. Thus, on the basis of the HST true distance modulus (7.090±0.114 mag, B02) one finds M_K=−0.550±0.118 mag, where the error is practically given by the uncertainty on the absolute trigonometric parallax.

Table 1. For each adopted metal content, we list the reference mass M_r and the evolutionary mass of ZAHB models with $\log T_e$=3.85 and 3.80. The mass values are in solar units.

Z	M_r	$M(3.85)$	$M(3.80)$
0.0001	0.75	0.796	0.852
0.0004	0.70	0.699	0.721
0.001	0.65	0.648	0.666
0.006	0.58	0.585	0.589
0.01	0.58	0.575	0.578
0.02	0.53	0.545	0.546

On the theoretical side, the predicted PLZ_K relation [eq. (1)] provides an independent estimate of the near-infrared absolute magnitude, once the metallicity, the mass, and the luminosity of the variable are known. As for the metallicity of RR Lyr, the measured iron-to-hydrogen ratio [Fe/H]=−1.39 (F98) implies a metal abundance $Z \sim 0.0008$, or slightly larger if the α-elements are overabundant with respect to iron (Clementini et al. 1995). Thus, accounting for ±0.15 dex as a typical uncertainty on the measured iron content, we estimate that the metallicity of RR Lyr should range from Z=0.0005 to Z=0.001. For the sake of the discussion, let us first adopt the upper limit Z=0.001.

According to this assumption, one can derive the stellar mass and luminosity on the basis of evolutionary constraints for Horizontal Branch (HB) models. Taking into consideration the discrepancies still affecting current theoretical predictions on the ZAHB luminosity (see, e.g., Castellani 1999; Ferraro et al. 1999; Caputo et al. 2000; VandenBerg 2000), as well as the increase in luminosity expected by post-ZAHB evolution, we end up with $\log L/L_{\odot}$=1.70±0.05. As for the stellar mass, thanks to the excellent agreement among the various authors about this parameter, from the evolutionary masses listed in the previous Table 1 we derive M=0.657±0.018$M_{\odot}$. We note that current uncertainties on the ZAHB luminosity and/or the evolutionary status of RR Lyr introduce an uncertainty on M_K of only 0.037 mag, while the uncertainty on the mass gives an even smaller error, namely $\sim$ 0.02 mag.

Including these uncertainties in quadrature, and since the pulsation period of RR Lyr is $\log P$=−0.2466 (Hardie 1955), the predicted PLZ_K relation supplies M_K=−0.512±0.045 mag, that is well within the error bar of the HST-based estimate (M_K=−0.550±0.118 mag), and with a much lower (formal) uncertainty mainly introduced by the uncertainty on the luminosity. By repeating this evaluation but with Z=0.0005, and adopting from the relevant literature the evolutionary values $\log L/L_{\odot}$=1.74±0.05 and M=0.697±0.020$M_{\odot}$, we obtain M_K=−0.570±0.046 mag. Eventually, the predicted PLZ_K relation and evolutionary constraints provide the following absolute K-magnitude for RR Lyr:

$$M_K = -0.541 \pm 0.044 \pm 0.029 = -0.541 \pm 0.062 \text{ mag}$$

where the final error ±0.062 mag includes the additional uncertainty on the adopted metal content (Z from 0.0005 to 0.001).

In conclusion, the predicted absolute K-band magnitude of RR Lyr is surprisingly similar to the HST-based estimate (M_K=−0.550±0.118 mag), and with a formal error that is a factor of two smaller than the one introduced by the HST absolute parallax. With K=6.54±0.04 mag, we find that the resulting true distance modulus of RR Lyr is μ_0=7.081±0.074 mag, yielding a "pulsation" parallax π_{puls}=3.835±0.131 mas which is very close to the trigonometric parallax measured by HST (π_{abs}=3.82±0.20 mas) and to the weighted average of HST, Hipparcos, and YPC5 measurements (π_{abs}=3.87±0.19 mas).

The extinction correction only marginally affects this result. With the already mentioned estimate $< A_V >$=0.07±0.03 mag provided by B02, the true distance modulus and pulsation parallax derived in the absence of reddening should be decreased by ~ 0.01 mag and increased by ~ 0.01 mas, respectively. To be more conservative, we should consider also the alternative values given by B02 ($< A_V >$=0.11±0.10 mag) and by F98 ($E(B-V)$=0.06±0.03 mag), adopting $< A_V >$=0.12±0.10 mag as a safe estimate of the extinction correction to RR Lyr. In such a case, the true distance modulus is μ_0=7.068±0.074 mag and the pulsation parallax is π_{puls}=3.858±0.131 mas. Once again, the pulsational estimate is quite similar to direct trigonometric parallaxes and with a total formal error well below the intrinsic uncertainty of the HST measurement.

3 FINAL REMARKS

It has been shown that the predicted PLZ_K relation for fundamental RR Lyrae stars and current evolutionary constraints on the mass and luminosity of HB models supply for RR Lyr itself a "pulsation" parallax surprisingly close to the HST measurement and to the weighted average of HST, Hipparcos and YPC5 measurements, and with a better (formal) accuracy ($\sigma_\pi/\pi \sim 3.5\%$). We would like to note that without the uncertainty on the adopted metal content ($0.0005 \leq Z \leq 0.001$), the error budget on the pulsation parallax would be smaller ($\sigma_\pi/\pi \sim 2\%$). Thus, if and when the metallicity of RR Lyr will be firmly established, the intrinsic uncertainty on the pulsation parallax could be reduced to roughly one third of current HST direct measurement ($\sim$ 5%).

Since the pulsation parallax is well within the error box of the HST measurement, we can conclude that for not heavily reddened RR Lyrae stars the theoretical PLZ_K relation works *at least* as good as HST, almost unaffected by uncertainty on the extinction correction. Also for heavily reddened variables, the pulsation approach could supply distance determinations as accurate as HST ($\sim$ 5%), provided that the extinction correction is known with sufficient accuracy ($\delta A_V \leq \pm 0.8$ mag). This means that the PLZ_K relation could be soundly adopted to estimate absolute distances to RR Lyrae stars in Baade's window as well as in highly reddened regions of the Galactic bulge.

However, before claiming that the pulsation approach yields distance estimates more precise than trigonometric parallaxes, we need further direct parallax measurements to exclude the possible occurrence of (small) systematic errors in the adopted (complicated) theoretical scenario. In the meanwhile, waiting also for future astrometric missions such as SIM, and GAIA, the PLZ_K relation seems actually the only viable means to get RR Lyrae distances in the Local Group, as accurate as the quoted HST result for the nearby variable RR Lyr.

Finally, we wish to mention that although the HST parallax estimate does supply the distance to RR Lyr with an unprecedented accuracy, the resulting absolute visual magnitude of this variable cannot firmly constrain the zero-point of the M_V-[Fe/H] relation for RR Lyrae stars, nor discriminate among the deceptive discrepancies affecting current theoretical predictions on HB evolutionary models, *even if the interstellar extinction to RR Lyr is firmly known.* As a matter of fact, according to the HST parallax (i.e., μ_0=7.090±0.114 mag) and by adopting V=7.76 mag (F98) together with the new extinction correction $< A_V >$=0.07±0.03 mag measured by B02, one derives for RR Lyr an absolute visual magnitude M_V=0.60±0.118 mag that is still affected by a large uncertainty. On the other hand, by adopting this extinction correction (i.e. K_0=6.532±0.040 mag) and by taking at the face value the predicted near-infrared absolute magnitude (M_K=−0.541±0.062 mag), one would derive μ_0=7.073±0.074 mag and M_V=0.617±0.079 mag. On this basis, one can foresee that the application of the predicted PLZ_K relation to a large sample of well-studied RR Lyrae stars that cover a wide metallicity range and present accurate K-band light curves will provide sound constraints on the slope of the M_V-[Fe/H] relation, as well as on the zero-point of the RR Lyrae distance scale if systematic errors can be excluded.

Acknowledgments: This work was supported by MIUR-Cofin 2000, under the scientific project "Stellar Observables of Cosmological Relevance".

REFERENCES

Benedict G. F. et al., 2002, AJ, 123, 473 (B02)
Bono G., Caputo F., Castellani V., Marconi M., Storm, J., 2001, MNRAS, 326, 1183 (Paper I)
Caputo F., Castellani V., Marconi M., Ripepi V., 2000, MNRAS, 316, 819
Cardelli J. A., Clayton G. C., Mathis J. S., 1989, ApJ, 345, 245
Cassisi S., Castellani V., Degl'Innocenti S., Weiss A., 1998, A&AS, 299, 267
Castellani V. 1999, in Globular Clusters, ed. C. Martinez Roger, I. Perez Fournon, & F. Sanchez (Cambridge: Cambridge Univ. Press), 109
Castelli F., Gratton R.G., Kurucz R. L., 1997a, A&A, 318, 841
Castelli F., Gratton R.G., Kurucz R. L., 1997b, A&A, 324, 432
Clementini G., Carretta E., Gratton R., Merighi R., Mould J.R., McCarthy J.K., 1995, AJ, 110, 2319
Fernley J.A., Barnes T.G., Skillen I., Hawley S.L., Hanley C.J., Evans D.W., Solano E., & Garrido R., 1998a, A&A, 330, 51 (F98)
Fernley J.A., Skillen, I., & Burki, G. 1993, A&AS, 97, 815
Ferraro F.R., Messineo M., Fusi Pecci F., de Palo M. A., Straniero O., Chieffi A., Limongi, M. 1999, AJ, 118, 1738
Groenewegen M.A.T., & Salaris M. 1999, A&A, 348, L33
Hardie R.H., 1955, ApJ, 122, 256
Longmore A.J., Dixon R., Skillen I., Jameson R.F., Fernley, J.A., 1990, MNRAS, 247, 684 (L90)
Perryman M.A.C., et al., 1997, A&A, 323, 49
van Altena W.F., Lee, J.T., Hoffleit. E.D., 1995, Yale Parallax Catalog (4th ed.; New Haven, CT: Yale Univ. Obs.) (YPC5)
VandenBerg D.A. 2000, ApJS, 129, 315